



INSTITUTE FOR DEFENSE ANALYSES

## **Improving Reliability and Operational Availability of Military Systems**

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## **PREFACE**

This document was prepared for the Director, Program Analysis and Evaluation, under a task titled “Technical Analyses for Army and Marine Corps/SOCOM Systems.”



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# **EXECUTIVE SUMMARY**

## **INTRODUCTION**

One of the major objectives of the Future Combat System family of military vehicles is to achieve high reliability and operational availability. The proposed means of achieving this objective is a prognostics-based approach to maintenance. That is, based on prediction of remaining life, parts vulnerable to failure are replaced just before they fail or before an upcoming mission. This paper presents analysis results that show how the prognostics maintenance strategy affects vehicle reliability and operational availability, contrasts this approach with traditional maintenance approaches (replacing the parts after they break and at set time intervals), and underscores benefits and limitations of each strategy.

## **METHOD**

In simultaneous-replacement-based maintenance, parts are replaced at set intervals, regardless of their condition. We evaluate the effect of replacement frequency on operational availability and costs (which are assumed to be proportional to the number of spare parts required to maintain the system). We assume that the prognostic capability exists for a fraction of all critical parts (in the analysis, this fraction is treated as a parameter varying from 0 to 1). We assess the effect of this strategy on operational availability and associated costs in terms of the number of spare parts required.

To evaluate and compare these two maintenance approaches, we constructed a Monte Carlo model to simulate the operation of a system composed of 300 platforms. The model computes the reliability of such a set of multiple platforms, where each platform is composed of a number of identical critical parts, operated over a given mission period, with a specified part-replacement strategy.

To establish a baseline, the system of 300 platforms was first simulated in the replace-as-needed mode, with instantaneous replacement of failed parts. We then ran the simulation for the simultaneous-replacement-based maintenance strategy, using various simultaneous-replacement frequencies. Finally, we ran the simulation for the prognostics-based maintenance strategy, using various prognostic ratios (the ratio of the number of

critical parts for which the remaining life can be predicted to the total number of critical parts).

We evaluated each strategy in terms of administrative and logistic delay time and operational availability, among other parameters.

## **CONCLUSIONS**

The simultaneous replacement of all mission-critical parts increases operational availability over a specified period of time. It can be done at regular intervals or just before an upcoming mission to increase the system pulse reliability. Frequent simultaneous replacements as a maintenance strategy will lead to an increased average operational availability over extended time periods even for low-reliability systems, but it will also result in significant costs, the result of replacing most parts prematurely and underutilizing their service life. While the risk of failure is reduced because the platform now has new parts, the replaced parts are thrown away even though most of them still have some (in many cases substantial) useful life left.

The prognostics approach is a more effective way to maintain desired operational availability. It allows reduced administrative and logistic delay times by anticipating upcoming failures and preparing the necessary parts in advance. In addition, the prognostics capability allows for intelligent maintenance—replacing only those parts whose remaining lifetime has reached a critical value. The prognostics approach, therefore, allows full utilization of each part's service life; this operational availability increase is obtained at significantly lower cost (number of spares) than that of the frequent simultaneous-replacement maintenance strategy.

One of the main operational benefits of the prognostics approach is that it leads to potentially failure-free missions because it allows field commanders to select only those platforms whose operational availability exceeds the duration of the upcoming mission.

## I. INTRODUCTION

Research presented in this paper is motivated by the question of how to achieve high reliability and operational availability of complex systems. Significant operational benefits are to be gained by employing highly reliable military assets. A brief history of U.S. military reliability objectives and major reasons why achieving high reliability is so important are described in [1] and summarized here as follows: (1) maintaining weapons systems consumes a significant portion of the total defense budget; (2) mission reliability is a key factor in determining system effectiveness; (3) the sustainable level of system readiness is in large measure determined by its reliability and maintainability characteristics.

In the current effort on developing future combat systems (FCS) family of military vehicles, achieving high operational availability is one of the major objectives [2]. To this end, reliability requirements of the new military platforms have been significantly increased. To achieve increased reliability and operational availability, development of a prognostics-based approach that will utilize “an embedded mission readiness system” is proposed. “This system will monitor the status of mission critical parts...The embedded readiness system will include the capability to forecast the future state of the FCS system...” [ref. 2, pp. 58–59].

In this paper, we examine ways to improve reliability of the complex systems and the relationship between a system’s reliability and its operational availability. We investigate in detail two approaches for achieving and maintaining high operational availability of military systems: simultaneous replacement of mission-critical parts and prognostics asset-management strategies.



## II. PROBLEM FORMULATION

### A. SYSTEM RELIABILITY

Consider a military system (e.g., a vehicle) with a number of mission-critical parts. The parts are mission critical in the sense that failure of one of the parts results in overall system being unavailable for use. We are interested in estimating the mission availability of this system based on the reliability of its parts. In our analysis, we assume that the parts operate independently (i.e., operation and failure of one of the parts does not affect the operation of other parts). We also assume that the parts are connected in series, meaning that if one or more parts fail, the system will no longer be operational.

The reliability of such a system with  $n$  components can be found as follows:

$$R(t) = (1 - F_1(t)) \cdot (1 - F_2(t)) \cdots (1 - F_n(t)) = \prod_{i=1}^n (1 - F_i(t)) \quad (1)$$

where  $F_i(t)$  is the cumulative failure distribution function for  $i$ th part:

$$F_i = \int_0^t f_i(t) dt \quad (2)$$

and  $f_i(t)$  is the  $i$ th part life's probability density distribution. The overall system reliability,  $R(t)$ , can in some cases be expressed analytically in a closed form. For example, when the individual parts fail exponentially (i.e.,  $f_i(t) = \lambda_i \exp(-\lambda_i t)$ ,  $\lambda_i$  being the part failure rate), the system reliability can be expressed as  $R(t) = \exp(-\bar{\lambda} t)$ , where  $\bar{\lambda} = \sum_{i=1}^n \lambda_i$ . In general, however, the expression for  $f_i(t)$  depends on the operating conditions and failure mechanisms of the part, and equation (1) can only be solved numerically.

### B. OPERATIONAL AVAILABILITY

In addition to considering the system reliability, we also investigate the effect of prognostics on operational availability ( $A_o$ ), which is defined as the ratio of the time the system was available for operation to the total mission time [3]:

$$A_o = 1 - \frac{T_d}{T_m} \quad (3)$$

where  $T_d$  is the system down time and  $T_m$  is the total mission time. The down time of the system is determined by the number of system failures during the mission (i.e., its reliability) and the time it takes to bring the system back to operational status. Repair times and simultaneous-replacement policies have a significant impact on  $A_o$ . A detailed discussion on this subject is given in [4].

## C. PARTS REPLACEMENT STRATEGIES

### 1. Simultaneous Replacement of Mission-Critical Parts

The strategy of *simultaneous replacement of mission-critical parts* is, as its name suggests, the periodic, complete, and simultaneous replacement of only those parts that cause the system (or vehicle) to be inoperable if one or more of them fail. (We refer to this strategy as “simultaneous replacement” hereinafter.) To evaluate the effect of simultaneous replacement on the vehicle operational characteristics, consider a maintenance policy with an operational time between simultaneous replacements equal to  $T$ . At time  $t = T$ , the system reliability drops to  $R(T)$ , at which point the system-critical parts are replaced by new parts. Reliability just before the simultaneous replacement can be determined as follows:

$$R(T) = \prod_{i=1}^n \left(1 - \int_0^T f_i(t) dt\right) \quad (4)$$

Since the replaced parts are assumed to be as good as new, the system reliability just after the simultaneous replacement is brought back to 1. The frequent-simultaneous-replacement approach may be a way to maintain high average system reliability, but it could lead to prohibitively high life-cycle costs because it results in many parts being replaced before the end of their useful service life.

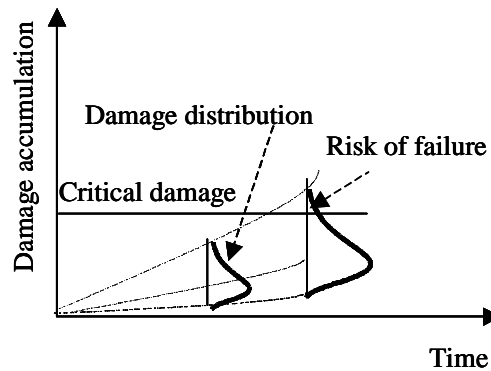
### 2. Prognostics

A discussion of the prognostics approach to maintenance of military systems and a description of a current DARPA effort focused on developing prognostics technologies can be found in [5]. An example of a prognostics approach applied to helicopter propulsion is described in [6]. Three basic prognostics strategies can be distinguished: the traditional risk-based approach, failure-precursor-based approach, and physics-of-failure approach [7].

The risk-based approach is based on the service life distribution of a part (assumed or known from its operational history). When the risk of operational failure



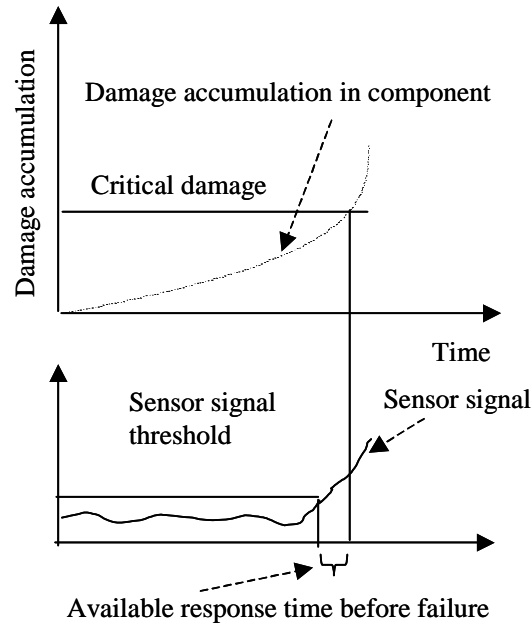
reaches a typically very small number, the system operation is stopped, and the part is replaced. (This approach is routinely used on aircraft for life-critical parts.) Figure II-1 is a schematic description of this approach.



**Figure II-1. Risk-Based Approach**

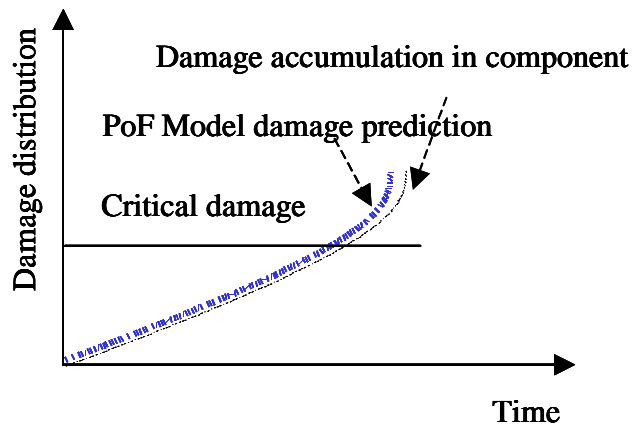
The risk of failure in this case can be approximated by the area under the curve, which describes a probability density distribution of the damage reaching critical size. Such a curve can, for example, describe a distribution of possible crack sizes at a certain location of a disc or blade in a turbine jet engine after a number of flights. As the number of flights increases, the distribution of possible crack sizes changes, reflecting increased probability of larger cracks. Eventually, there is a small but finite probability that the crack has reached a critical length, which is determined by material properties and upcoming loading conditions. The inspection interval times are set so that the parts are inspected just before the crack reaches critical size. The part is replaced in the event a defect is found or the part had flown a certain number of cycles, even if there is no defect found.

Figure II-2 is a schematic description of a precursor-based approach. It is applicable to situations when there is a degradation mechanism that can be observed and detected by a sensor. At some point during the vehicle operation, the damage-detection threshold is reached, indicating that damage has reached some level detectable by a sensor. In cases when this precursor time (i.e., the time between the progression of the damage from detectable to critical level) is long enough to plan ahead for the maintenance action, this is a useful approach. But in cases where a failure is detected just before it happens, the practical applicability is limited.



**Figure II-2. Precursor-Based Approach**

Figure II-3 depicts the physics-of-failure approach, an approach that has been widely reported in the literature (examples of applications of this approach to mechanical systems can be found in [7] and [8]). In this approach, it is assumed that structural loads are continuously monitored, and damage progression is modeled by a physics-of-failure model and validated by on- or off-line sensors. The physics-of-failure model predicts the state of damage and the remaining life for an assumed loading during an upcoming mission.



**Figure II-3. Physics-of-Failure Approach**

In this paper, we assume that the prognostics capability allows us to know the current damage state of the part and its remaining life. That is, we can deterministically predict when the part is going to fail.<sup>1</sup>

The prognostics approach allows a flexible maintenance strategy—replacing the part just before it fails or at some predetermined time interval before failure, which may be based on the upcoming mission duration or the availability of mechanics and spare parts. For example, if it is desired that no failures should take place during an upcoming mission, all parts with remaining life less than the upcoming mission duration time would be replaced.

#### **D. INVESTIGATION OBJECTIVES AND APPROACH**

The goal of the reported investigation is to evaluate the effect of prognostics on a system's reliability and its operational availability and compare those practices with traditional maintenance policies. To this end, we implemented a Monte Carlo modeling approach based on the following assumptions. First, we assumed that the platforms (or a set of military vehicles) under investigation have critical parts with the same failure probability density function. Second, we assumed that the critical part's service life has a Gaussian distribution. This choice is motivated by our goal to highlight the differences between the simultaneous replacement and prognostics approaches and to investigate the potential benefits of prognostics. To ensure realistic lifetime values, we used data from real-time military exercises to estimate the mean and standard deviation of the part's lifetimes [9].

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<sup>1</sup> This is obviously an idealized situation. In reality, there will be uncertainties associated with the upcoming mission conditions, operating environment, predictive models, and sensors. Quantification of these uncertainties is outside of the scope of this investigation.



### III. SIMULATION DETAILS

#### A. DESCRIPTION

We constructed a Monte Carlo model to simulate the operation of a system composed of a large number of platforms. The model computes the reliability for such a set of multiple platforms, where each platform is composed of a number of identical critical parts and is operated over a given mission period with a specified part-replacement strategy. Platform failure (mission abort) takes place when any one of the critical parts fails. The part failures are independent, and they have randomly distributed lifetimes. We investigated three part-replacement strategies: (1) replace as needed (our baseline), (2) simultaneous replacement at a specified interval, and (3) prognostics.

#### B. PART FAILURE LIFE DISTRIBUTION

In the model, any distribution may be used to describe the probability of part failure as function of time. For this study, we chose the Gaussian distribution:

$$P(x) = \frac{1}{\sqrt{(2\pi)\sigma}} \exp\left\{-\frac{(x - \mu)^2}{2\sigma^2}\right\}. \quad (5)$$

$P(x)$  is the probability that a part has lifetime  $x$  given the mean part lifetime  $\mu$  and standard deviation  $\sigma$ . The part lifetime  $\mu$  is a variable parameter, whose effect on reliability and operational availability we investigate. The standard deviation  $\sigma$  is held fixed at 0.25 percent of the mean part lifetime because variation of  $\sigma$  has only minor effect on  $A_o$  (see Appendix A).

#### C. IMPLEMENTATION OF PART-REPLACEMENT STRATEGIES

In the replace-as-needed maintenance strategy, parts are replaced as they fail, and the platform incurs repair time and administrative and logistic delay time (ALDT). The ALDT and repair time are randomly chosen from a Gaussian distribution with user-specified mean and standard deviation (The values for these distributions are chosen from the data for Army platforms [9].)

For the simultaneous-replacement maintenance strategy, all parts are replaced at the same time at user-specified time intervals. No ALDT associated with part delivery occurs because it is assumed that all the parts are prepared beforehand. Thus, only repair

times are randomly chosen from a Gaussian distribution. It is also assumed that all parts are repaired within the time it takes to fix the part with the longest repair time. In addition, if during the platform operation a part fails before the scheduled simultaneous-replacement interval occurs, the replace-as-needed strategy is applied to that particular part.

In the prognostics mode, the residual life of the part is assumed known in every instance. The parts could be repaired at any time during the service. In this investigation, the replacement time is chosen to be just before the part fails. No ALDT is incurred. The repair time is randomly sampled from a Gaussian distribution.

#### D. SIMULATION INPUT PARAMETERS

Table III-1 gives all the model input parameters used in the simulations.

**Table III-1. Input Parameters**

<b>Parameter</b>	<b>Value</b>
Operation time in years	2
Number of platforms	300
Number of parts	5, 10, 15, 20
Mean part lifetime in years	$\frac{1}{4}$ , $\frac{1}{2}$ , 1, 2
Part lifetime standard deviation as a percentage of mean lifetime	5, 10, 25, 50
All parts have the same failure distribution	Gaussian
Part repair time in hours (uncertainty)	4 (5%)
Part delivery time in hours (uncertainty)	12 (80%)
Simultaneous-replacement time interval as a percentage of part lifetime	50, 75, 90
Percentage of parts with prognostics capability	25, 50, 75, 100

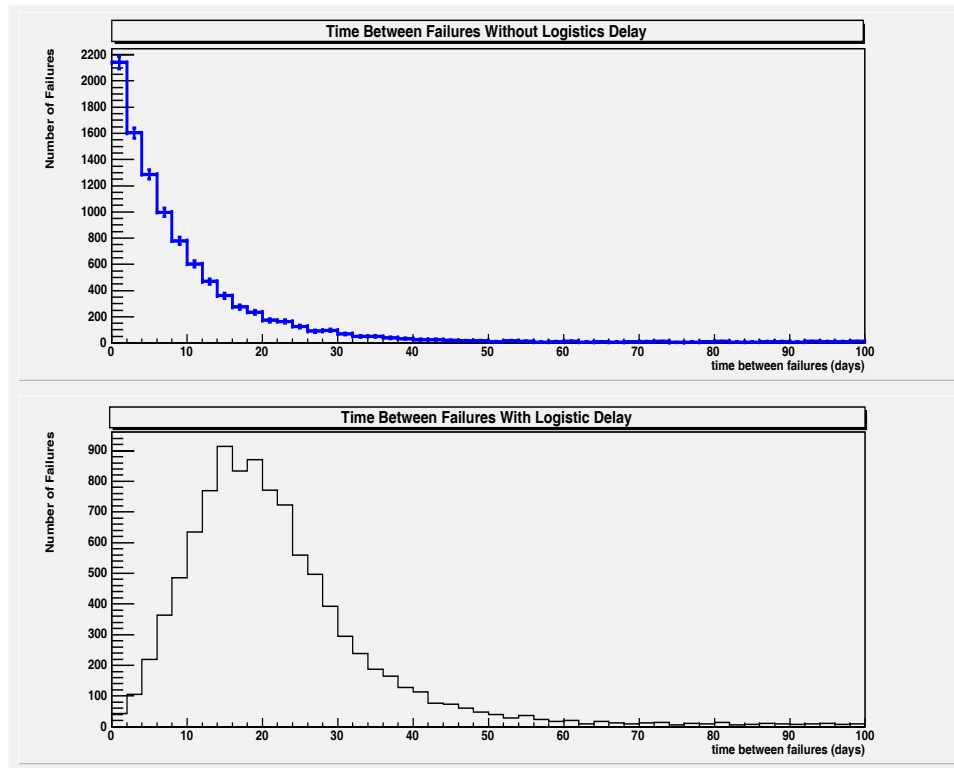
## IV. SIMULATION RESULTS

### A. REPLACE AS NEEDED

The system of 300 platforms was first simulated in the replace-as-needed mode, with instantaneous replacement of the failed parts. The upper plot of Figure IV-1 is a histogram of the times between platform failures. These results can be described by an exponential behavior with a reasonable accuracy: An exponential fit of the histogram is obtained when the meantime between failure (MTBF) of this system is  $10.0 \pm 0.1$  days. The MTBF is obtained by performing an exponential fit to the histogram, and the uncertainty is taken from the fit error. The observed system reliability behavior is in agreement with previous findings by Drenick [10], who showed that under appropriate conditions, complex systems fail in an exponential manner even though their individual parts behave according to other types of failure distributions. This happens when the system consists of a large number of parts, the parts are connected in series, and the part behavior is uncorrelated. The significance of this statement is that the reliability of the system under consideration can therefore be described by one parameter, MTBF, or its inverse, the failure rate,  $\lambda$ . It is therefore a reasonable practice for military platforms, which are systems with large numbers of parts.

The lower plot of Figure IV-1 depicts the behavior of the times between failure of a system with the added Gaussian-distributed ALDT and repair times.

Figure IV-2 shows the effect of decreasing the number and increasing the lifetime (or reliability) of individual parts on the total system reliability—the well-known design strategy for improving system reliability. As expected, as the part lifetime increases, the average platform MTBF also increases. The effect is more pronounced for a small number of parts. The error on the average MTBF for platforms composed of smaller numbers of parts with longer lifetime is larger than that of platforms with larger numbers of parts due to a less accurate fit to an exponential distribution. For platforms composed of large numbers of parts, even substantial improvement in the lifetime of individual parts results in only marginal increase in system reliability. The significance of this result is that a considerable design effort should be focused on reducing the number of reliability-critical parts.

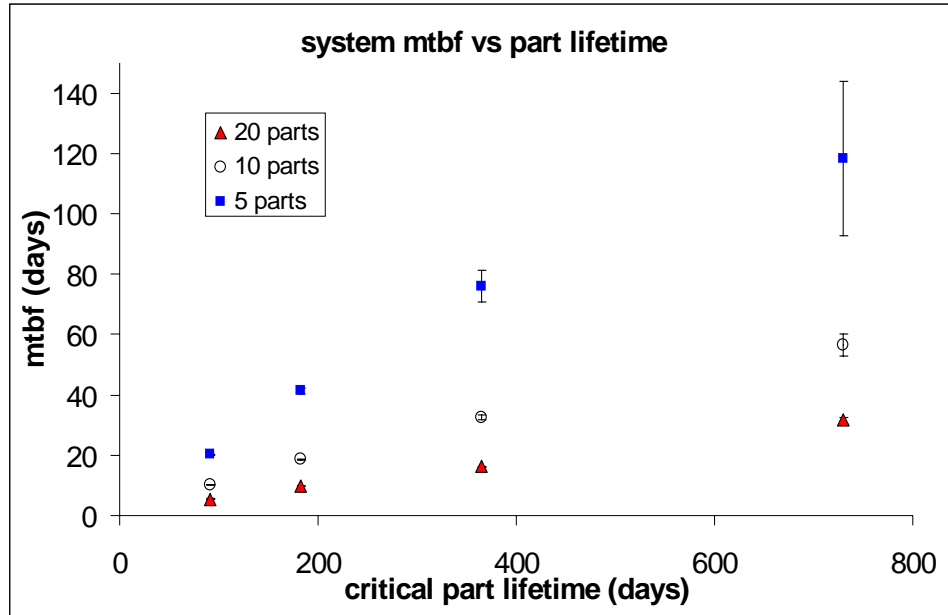


**Figures IV-1. Time Between Failures**

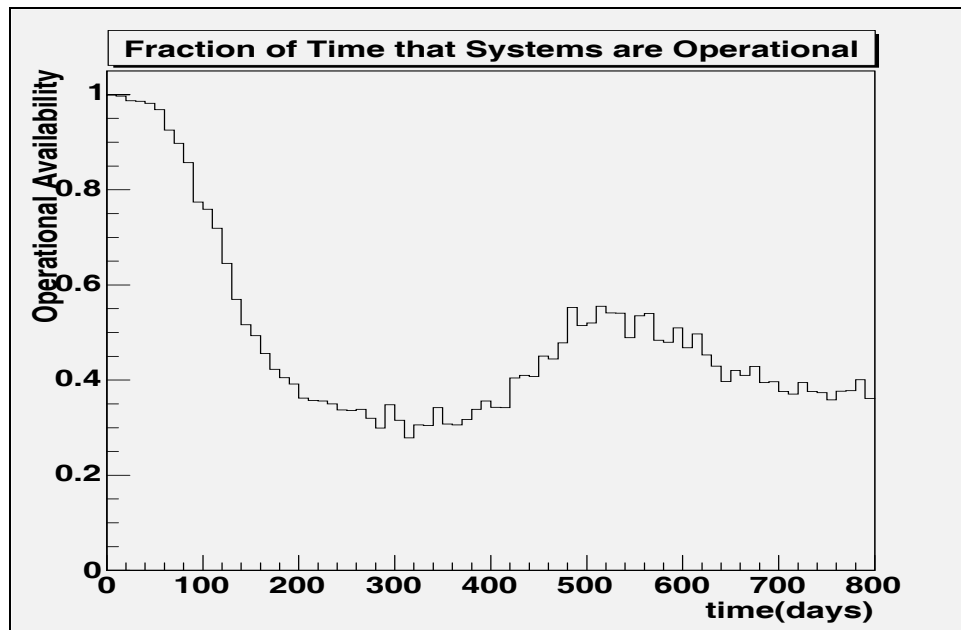
**The upper plot is a histogram of the time between platform failures without logistics delays for a system of 300 platforms, each composed of 20 critical parts with  $\frac{1}{2}$ -year lifetimes. The lower plot is the time between failures with logistics delay that includes both delivery and repair times.**

In real operational environments, delays in bringing a system back to operational status are primarily determined by ALDT, and so the system behavior can be described by its operational availability. Figure IV-3 depicts the operational availability as a function of time for 300 platforms, each composed of 20 critical parts. The operational availability starts at 1 in the beginning of the platform's service, and then it exhibits a periodic behavior eventually approaching some asymptotic value. The instantaneous  $A_o$  can be averaged over a 2-year mission time to yield  $0.48 \pm 0.02$ .





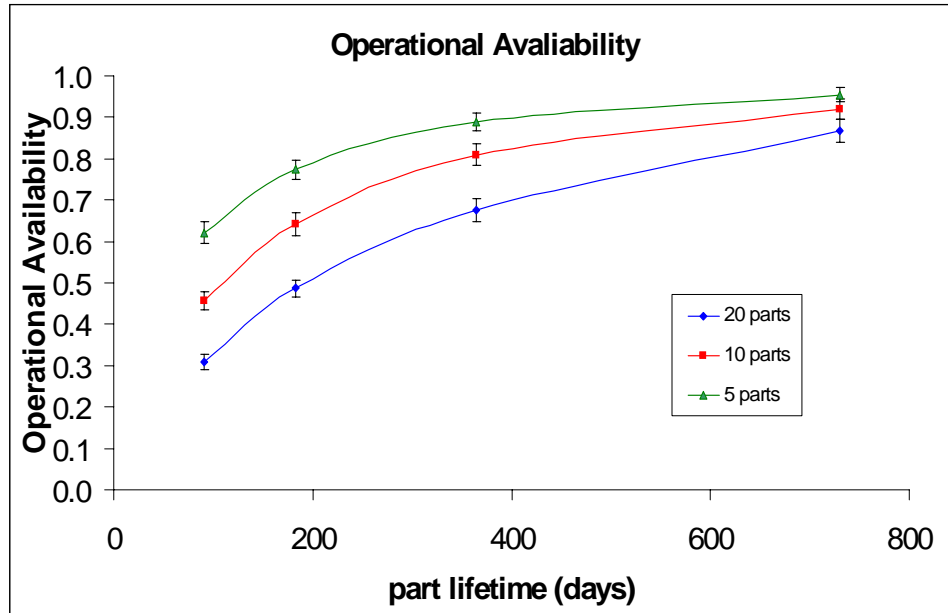
**Figure IV-2. System MTBF vs. Part Lifetime**  
Average MTBF for a system of 300 platforms as a function the number and lifetime of the critical parts that make up each platform.



**Figure IV-3. Operational Availability vs. Time—with ALDT**  
Instantaneous operational availability,  $A_o(t)$ , for a system of 300 platforms each composed of 20 critical parts with a lifetime of  $\frac{1}{2}$  year as a function of time.

Figure IV-4 shows the effect of the number and reliability of the individual parts on the average platform operational availability. As the reliability of the parts increases, the operational availability also increases. In the limit of very long part lifetimes, the operational availability approaches 1. These results demonstrate that, like the

instantaneous-replacement case (no repair and no ALDT), a significant tradeoff between number of parts and their reliability is preserved in a situation when ALDT and repair times apply.

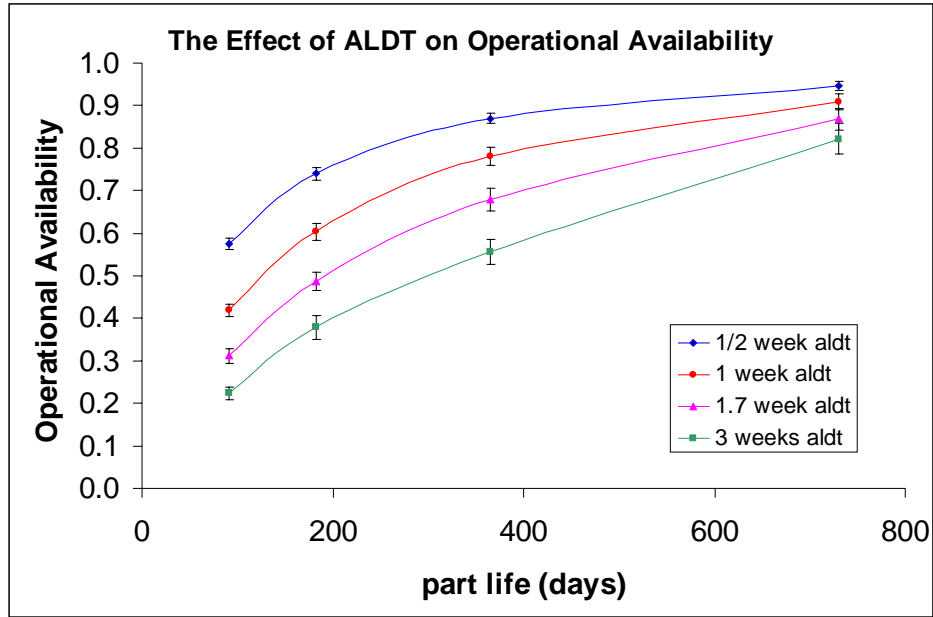


**Figure IV-4. Part Lifetime vs. Operational Availability**  
Average operational availability for a system of 300 platforms as a function the number and lifetime of the critical parts that make up each platform.

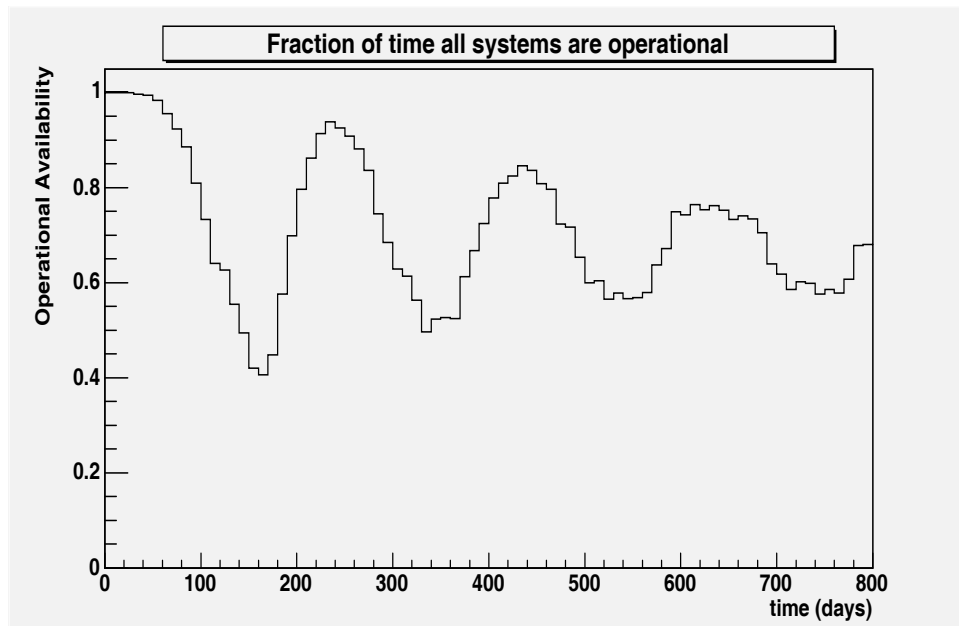
Figure IV-5 shows the effect of reducing ALDT on operational availability. Even with a relatively low part lifetime, the operational availability can be substantially improved by reducing ALDT. This means that while it might be very difficult to improve reliability of a platform itself by design, reducing its ALDT might be less of a challenge, leading to a practical way to achieve substantial improvement in operational availability.

## B. SIMULTANEOUS-REPLACEMENT STRATEGY

One of the possible strategies to improve operational availability is to replace the system-critical parts, all at the same time, at regular intervals. Figure IV-6 depicts results of the simulation of a system with a simultaneous-replacement frequency of 137 days (three-fourths of the part's lifetime). Under those conditions, the average operational availability over a 2-year time period is  $0.71 \pm 0.05$ , a significant improvement over  $0.48 \pm 0.02$ , the operational availability of a similar system without simultaneous replacements (Figure IV-3).

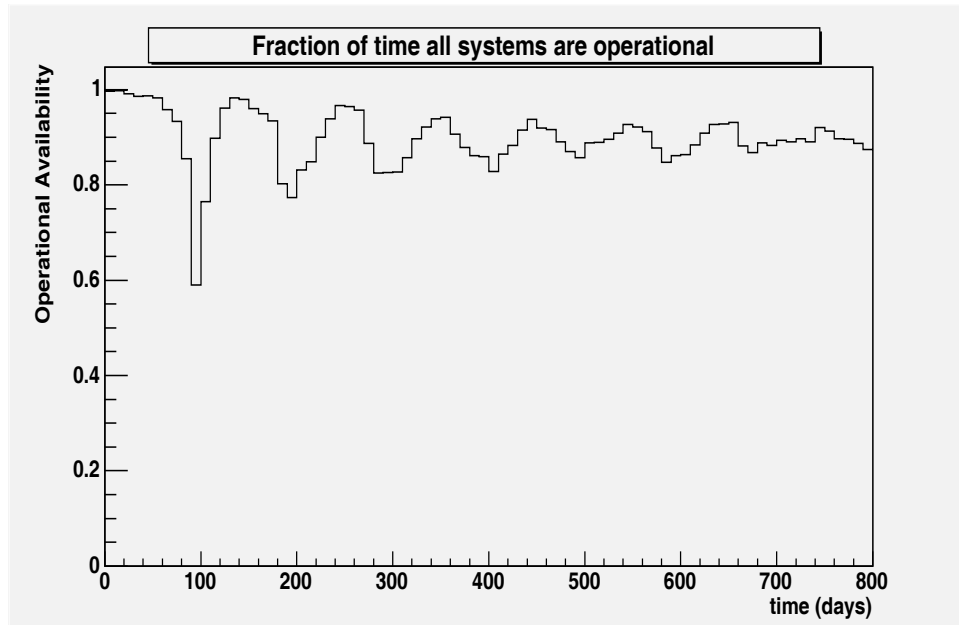


**Figure IV-5. ALDT vs. Operational Availability**  
Average operational availability as a function of critical part lifetime for various ALDTs for a system of 300 platforms, each with 20 critical parts.



**Figure IV-6. Operational Availability vs. Time—75% Lifetime Simultaneous-Replacement Frequency**  
Instantaneous operational availability with a platform simultaneous-replacement frequency of 137 days (75% of the lifetime of the critical parts that make up the platform) for a system of 300 platforms as a function of time. Each platform is composed of 20 critical parts with a mean and standard deviation of  $182.5 \pm 45.6$  days.

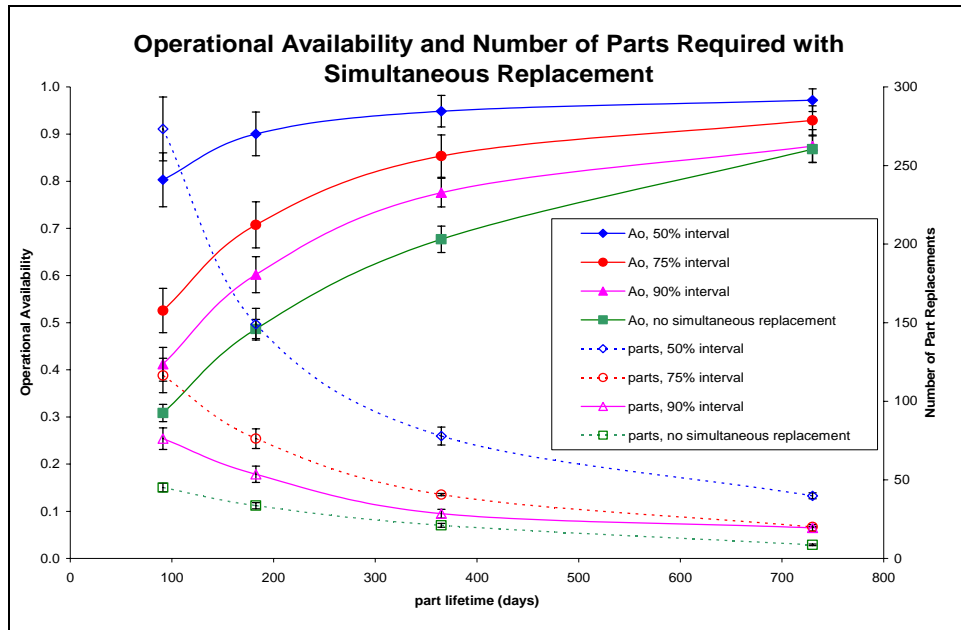
Figure IV-7 shows the effect of increasing the simultaneous-replacement frequency to one-half of the part's lifetime. In this case,  $A_o = 0.90 \pm 0.05$ . Increasing this frequency leads to a considerable improvement in operational availability.



**Figure IV-7. Operational Availability vs. Time—50% Lifetime Simultaneous-Replacement Frequency**  
**Instantaneous operational availability with a platform simultaneous-replacement frequency of 91.25 days (50% of the lifetime of the critical parts that make up the platform) for a system of 300 platforms as a function of mission time.**

While the simultaneous-replacement strategy does lead to high operational availability, it is important to recognize that the penalty for this approach is the high cost associated with replacing parts too often, thus underutilizing their service lives. A series of simulations were performed to illustrate the effect of increasing the simultaneous-replacement frequency on life-cycle costs. In this case, the life-cycle cost is assumed to be proportional to the number of parts changed during the platform operation.

Figure IV-8 depicts the operational availability of a system of platforms as a function of part lifetime; also shown is the number of spare parts required to maintain that system. For a platform with a given number of parts and their lifetimes, a maintenance strategy could be chosen based on desired operational availability and cost constraints. If no simultaneous replacement is performed, that is, if the system is allowed to operate until the part's failure (with a subsequent part replacement), the incurred cost is at a minimum, but operational availability is also limited. In particular, only platforms with very reliable parts (with mean lifetimes greater than 500 days) can achieve an operational availability over 75%.



**Figure IV-8. Operational Availability vs. Part Lifetime—Different Simultaneous-Replacement Frequencies**  
Average operational availability and the average number of replaced parts are shown as functions of part lifetime for a system of 300 platforms, with parts replaced at simultaneous-replacement intervals of 50%, 75%, and 90% of the critical part lifetime.

To improve the operational availability, a higher simultaneous-replacement frequency may be chosen. As this frequency increases, even the platforms with relatively low part lifetimes can reach a high operational availability. For example, if an operational availability greater than 90% is desired for a platform composed of parts with lifetimes of 180 days, the simultaneous replacement could be performed every 90 days (50% of the part's lifetime). In this case, however, the cost (the total number of parts that are replaced) of such a maintenance strategy is considerably higher than that for a platform with a part lifetime of 360 days.

To put these results into perspective, consider the reliability of current military platforms. The Stryker Infantry Carrier Vehicle has an MTBF of approximately 167 hours (~ 7.0 days) [11]. This is equivalent to a simulated system having 20 critical parts, each with a ½-year lifetime. The Bradley Fighting Vehicle has an MTBF of 133 hours, or about 5.5 days [11], which is equivalent to a simulated system with 20 critical parts, each having ¼- to ½-year lifetimes. The M1A2 Abrams main battle tank has an MTBF of 27 hours [11], which is equivalent to a simulated system with 30 critical parts, each having a 1-month lifetime. The implication is that to maintain a high operational availability for platforms with those relatively low reliabilities over long mission times would require frequent simultaneous replacements and significant cost. If the mission times are short, it

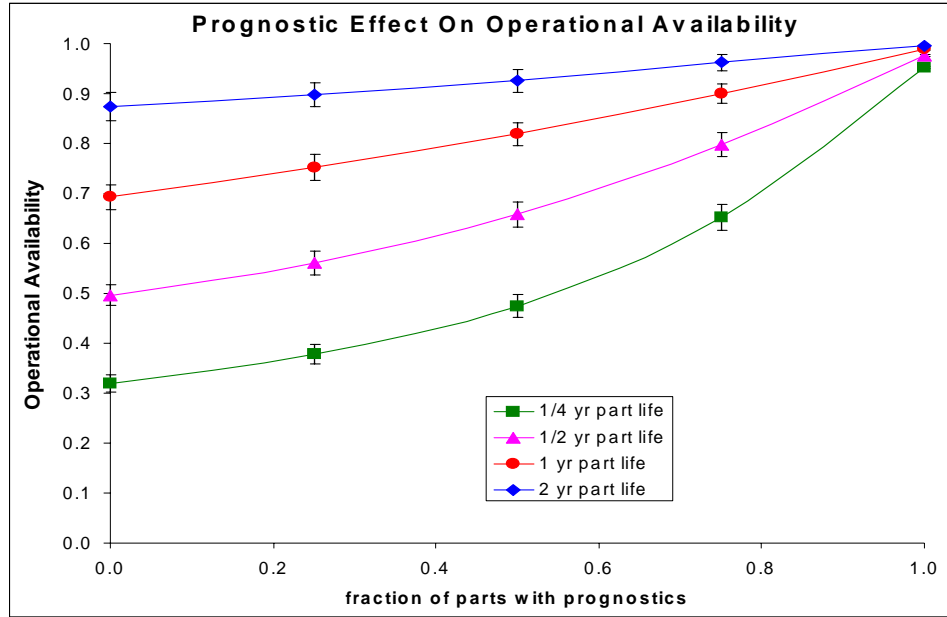
is possible to reduce the costs by performing the simultaneous replacements just before the mission, a so-called “pulse reliability” improvement. Note, however, that in this case the average operational availability over an extended period of time will still be low.

### **C. THE EFFECT OF PROGNOSTICS**

The prognostics capability in this investigation is described by the prognostics ratio,  $p$ , defined as a ratio of the number of critical parts for which the remaining life can be predicted to the total number of critical parts. Note that in general it is unlikely that all failures in a platform can be predicted. For example, most of the electronic parts fail randomly and not according to a wear-out law; hence no physics-of-failure prognostics can be implemented for those parts.

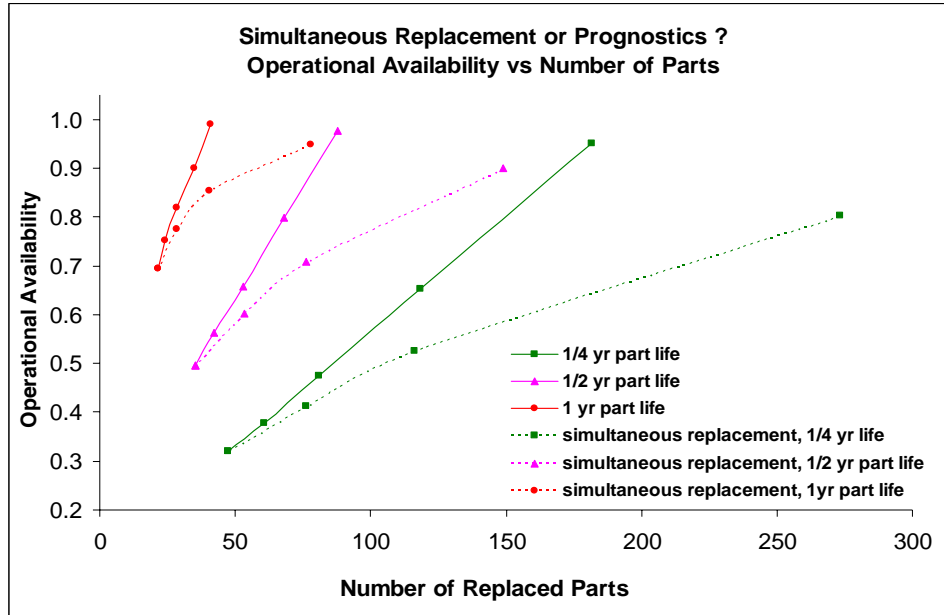
The benefits of the prognostics capability are twofold. When a part failure is anticipated, in the sense that its remaining life is known, the replacement part can be ordered in advance, reducing ALDT essentially to zero. This has a pronounced effect on improving operational availability. In addition, knowing the time to failure allows military commanders in the field to choose platforms that are theoretically capable of performing failure-free during the upcoming mission, as well as to schedule maintenance when spare parts and resources are available.

Figure IV-9 demonstrates the effect of prognostics on operational availability for systems with various part lifetimes. Note that the part lifetime plays an important role, even when the prognostics capability is implemented. For example, a Stryker vehicle with an MTBF of 167 hours is equivalent to a simulated system of 20 critical parts each with a ½-year lifetime. The operational availability of such a system is about 50%. Now if prognostics were to be implemented on 12 of 20 of those parts ( $p = 0.6$ ), the operational availability of such a system would substantially increase to 70%. The significance of this result is that the prognostics approach by itself should not be considered a way to improve vehicle reliability. Rather, the prognostics approach is a means to improve operational availability, which is achieved by anticipating part failures and improving efficiencies in replacing parts. Even with prognostics, however, the operational availability is limited by the inherent system reliability, which is a function of vehicle design and operating conditions.



**Figure IV-9. Prognostic Effect on Operational Availability**  
Average operational availability as a function of the fraction of critical parts with prognostics for a system of 300 platforms each with 20 critical parts.

Figure IV-10 compares the number of required replacement parts needed to maintain a system at a desired operational availability when prognostics are applied with the number needed when simultaneous replacement is applied. The prognostics part-replacement strategy produces higher operational availability values as the prognostic ratio,  $p$ , and increases from 0 to 1 in steps of 0.25. The simultaneous-replacement strategy produces higher operational availability values as the simultaneous-replacement frequency increases, starting from no-simultaneous-replacement case and then increasing from 90%, to 75%, and to 50% of the critical part lifetime. Note that in both cases, additional parts are needed to maintain low-reliability systems at high operational availability. However, the prognostics strategy requires fewer replacement parts. For systems composed of less reliable parts, this difference is substantial. Therefore, using prognostics is a much more effective and potentially less expensive approach to achieving high operational availability.



**Figure IV-10. Simultaneous Replacement or Prognostics—  
Operational Availability vs. Number of Parts**

Average operational availability as a function of the number of replaced parts and their lifetimes for the simultaneous replacement and prognostic part-replacement strategies for a system of 300 platforms composed of 20 parts each. The solid lines have 5 points indicating the prognostic ratios of 0%, 25%, 50%, 75%, and 100% (moving from lower left to upper right). The dashed lines represent the frequency of system simultaneous replacements based on the percentage of the critical parts total lifetime. Moving from lower left to upper right, the four points are, no simultaneous replacement performed, 90% of part life, 75% of part life, and 50% of the part life.



## V. CONCLUSIONS

1. The reliability of complex systems with many independently operating parts connected in series can be significantly improved by reducing the number of critical parts. Improving the individual part reliability also leads to an increase in the overall system reliability, but this effect is less pronounced for systems with a large number of parts.
2. Operational availability of the military vehicles is significantly affected by ALDT and repair times. Improving the maintenance practices, that is, decreasing the delay and repair times, is an effective means of improving the operational availability.
3. Performing simultaneous replacements increases operational availability over a specified operational time. It can be done at regular intervals or just before an upcoming mission to increase the system pulse reliability. Frequent simultaneous-replacement maintenance will lead to an increased average operational availability over extended time periods even for low-reliability systems, but it will also result in substantial costs, the result of replacing many parts and underutilizing the their service life.
4. The prognostics approach allows reducing ALDT and improving operational availability by anticipating failure and preparing the necessary replacement parts. In addition, the prognostics capability allows for intelligent maintenance—replacing only those parts whose remaining lifetime has reached a critical (predetermined) value. In this case, the operational availability increase is obtained at significantly lower cost (in terms of the number of spares) than that of the simultaneous-replacement maintenance strategy. The prognostics approach can in theory lead to failure-free missions because it allows field commanders to select only those platforms whose operational availability exceeds the duration of the upcoming mission.



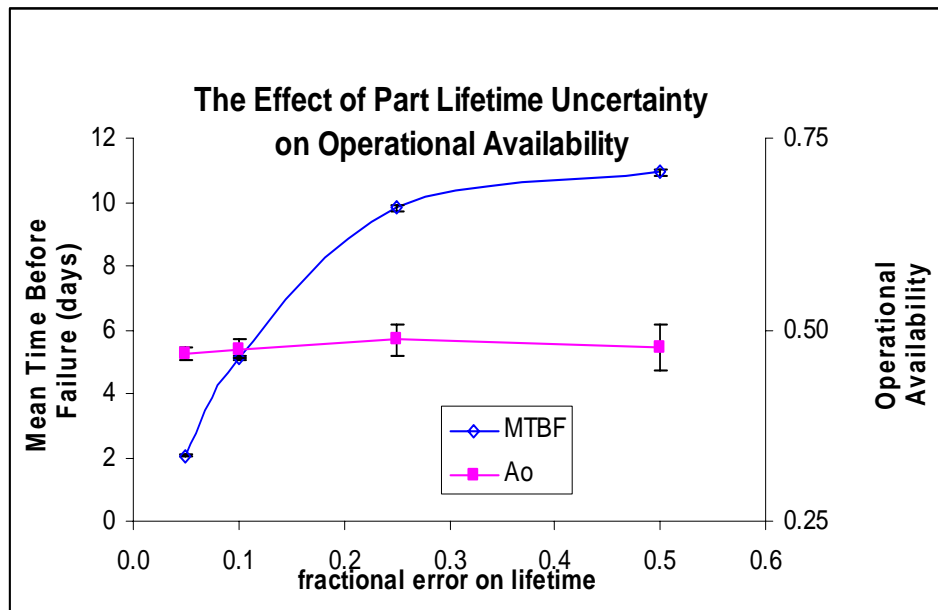
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## APPENDIX A

### THE EFFECT OF THE PART LIFETIME UNCERTAINTY ON OPERATIONAL AVAILABILITY



**Figure A-1. Effect of Part Lifetime Uncertainty on Operational Availability**  
**Effect of increasing the fractional uncertainty of the critical part lifetime (i.e., ratio of the standard deviation to the mean lifetime) on Mean Time Before Failure and Operational Availability for a system of 300 platforms, each made up of 20 critical parts with ½-year lifetime.**

The results in Figure A-1 show that the average operational availability is only weakly dependent upon the uncertainty in the critical part lifetime. Instead, the average operational availability is dependent on the total number of part failures for a given mission time, not how far apart the failures are in time. In the tests performed in this study, the mission time is long compared with the part lifetime. So even as the lifetime uncertainty gets broader, the total number of failed parts over the mission remains fixed, and operational availability stays constant. In addition, the mean time between failure gets longer as the fractional error on the lifetime is increased. This is due to the broadening of the time before failure distribution, such as Figure IV-2, which depends upon the broadening of the underlying lifetime distribution for each part. But the spreading of the underlying lifetime distribution also forces the system failures to occur

at increasingly earlier times than would occur with parts with smaller uncertainty in their lifetimes.

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